

Tenth-order rational-harmonic frequency multiplication and detuning of optical pulse injection-locked erbium-doped fiber laser

Gong-Ru Lin and Jung-Rung Wu

The jitter and frequency-detuning dynamics of a 10-GHz rational-harmonic frequency-multiplied pulse train generated from an erbium-doped fiber laser (EDFL) is studied. The EDFL is self-feedback seeded and optically injection locked by a gain-switched laser diode (GSLD) with a pulse width and an average power of 17.6 ps and 0.2 mW, respectively, at a repetition frequency of 1 GHz. The repetition frequency of the optical pulse train can be tenth-order multiplied by a slight detuning of the repetition frequency of the GSLD to match the rational-harmonic injection-locked condition of the EDFL. As the repetition frequency is multiplied from 1 to 10 GHz, the peak power, the pulse width, and the frequency-detuning bandwidth of the injection-locked EDFL pulses decrease from 1.2 to 0.3 W, from 40 to 21 ps, and from 40 to 9 kHz, respectively. The timing jitter of the injection-locked EDFL repeated at 1 GHz remains unchanged (<0.5 ps) within the detuning bandwidth, which inevitably increases to 1.2 ps after tenth-order multiplication. © 2005 Optical Society of America

OCIS codes: 140.3520, 060.2320.

1. Introduction

High-repetition-rate optical pulse generation and multiplication techniques have been investigated extensively for applications such as optical time-division multiplexing and soliton transmission systems. Some novel approaches to pulse generation, such as fiber dispersion,¹ intracavity fiber Fabry–Perot filtering,² optical-pulse injection,^{3,4} and all-optical modulation⁵ mode-locking schemes, have been investigated. Mak *et al.*⁵ previously demonstrated tunable optical pulse-train generation of a gain-switched Fabry–Perot laser diode (GSLD), using fiber-dispersion-based repetition-rate multiplication.^{6,7} The phase noise and jitter dynamics of mode-locked and regeneratively mode-locked erbium-doped fiber lasers (EDFLs) have been studied in more detail by Gupta *et al.*⁸ However, rational-harmonic frequency multiplication and detuning dynamics, and the phase noise as well as the jitter performance of

EDFLs that are injection locked by GSLDs, have been less discussed. In this paper we study the injection-locking bandwidth and the jitter response of a 10-GHz repetitive pulse train generated from EDFL injection locking by a GSLD at 1 GHz. Such a tenth-order rational-harmonic frequency-multiplied optical pulse train from the EDFL is shown to exhibit relatively low supermode noise and jitter and high average output power with fairly good stability at repetition frequencies of as much as 10 GHz. The behavior of the 10-GHz rational-harmonic frequency-multiplied EDFL pulses in terms of pulse width, peak, and average power; single-sideband phase noise; and relative timing jitter are discussed relative to the detuning of the pulses' repetition frequency from the closest harmonic resonant frequency of the EDFL cavity.

2. Experimental Setup

The optically pulse-injection-locked and rational-harmonic frequency-multiplied EDFL system is shown in Fig. 1. The active medium in the EDFL is a homemade erbium-doped fiber amplifier (EDFA) with a 6-m-long Er-doped fiber (Lucent, R37005), which is bidirectionally pumped by two 980-nm laser diodes with 140-mW power. The EDFA is self-feedback seeded (closed-loop) to achieve EDFL operation and is simultaneously injection locked by a commercial fiber-pigtailed Fabry–Perot laser diode

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Received 24 March 2004; revised manuscript received 24 October 2004; accepted 16 November 2004.

0003-6935/05/122416-05\$15.00/0

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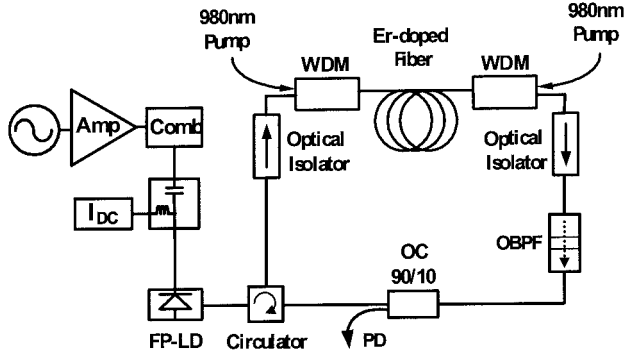


Fig. 1. Schematic diagram of regenerative EDFL injection locking with a gain-switched FP-LD: Amp, microwave power amplifier; Comb, electrical pulse (comb) generator; OBPF, optical bandpass filter; OC, optical coupler; PD, photodetector; WDMs, wavelength-division multiplexing couplers.

(FP-LD) with a central wavelength of 1558 nm at a specified temperature of 35 °C via a 50/50 optical coupler. Versatile optical couplers with selected power-splitting ratios can be employed as output couplers of EDFLs. An EDFL with 90% output is preferred for maximum output power. All the components were fusion spliced by Corning SMF-28 single-mode fibers. An EDFL cavity length of 50 m results in a fundamental cavity frequency (f_c) of 4.48 MHz. For gain-switching operation, the FP-LD with longitudinal mode spacing of 1.2 nm is biased near threshold and modulated by an amplified radio frequency sinusoidal signal of 28 dBm at 1 GHz generated from a radio frequency synthesizer (Hewlett-Packard, HP83620) by a biased-T circuit. The driving condition of the GSLD is optimized to produce narrow-pulse-width, low-side-mode peaks. The EDFL can thus be injection locked at its harmonic frequency by precise adjustment of the repetition frequency of the GSLD, which gives rise to a symmetrical pulse shape when the repetition frequency of the GSLD is coincident with the harmonic frequency of the EDFL. The single-sideband (SSB) phase noise spectrum is measured by a microwave spectrum analyzer (Rohde & Schwarz, FSEK-30) with a resolution bandwidth of 1 Hz. By subtracting the SSB phase noise spectrum of the high-order harmonic component from that of the fundamental component in the injection-locked EDFL pulses, the absolute SSB phase noise density and the corresponding timing jitter $\sigma(f)$ can be determined from the following equation with the desired integral region:

$$\sigma(f) = \frac{1}{2\pi f_0} \left(2 \int_{f_L}^{f_H} \{ [L_1(f) - L_n(f)] / (n^2 - 1) \} df \right)^{1/2},$$

where $L_1(f)$ and $L_n(f)$ are the SSB phase noise spectrum measured at the fundamental and its n th-harmonic repetition frequencies.

3. Results and Discussion

The proposed GSLD injection-locked EDFL system is completely different from previously reported mode-locked EDFLs that use FP-LDs as optical modulators, as a FP-LD already has gain-switched lasing in our case. The pulse shapes of a GSLD and an injection-locked EDFL repeated at 1 GHz are shown in Fig. 2(a). The GSLD exhibits a pulse width and an average power of 17.6 ps and 210 μ W, respectively. When the repetition frequency of the GSLD coincides with the 223th harmonic (\sim 996 MHz) of the EDFL cavity fundamental mode, the pulse width, peak, and average powers of a perfectly injection-locked EDFL measured at the 90% coupler are 41 ps, 1.8 W, and 95 mW, respectively. The GSLD pulse is broadened but slightly reshaped to be more nearly symmetrical during the regenerative amplification process in the EDFL. We can also observe the frequency-multiplied pulse train of the EDFL by detuning the repetition frequency of the GSLD to match the specific modulation frequency $f_m = (n + 1/p)f_c$, where n and p are the harmonic and the rational harmonic orders, respectively. Such an operation is identical to that for actively rational-harmonic mode-locked lasers. For example, second-, fifth-, and tenth-order rational-harmonic frequency-multiplied EDFL pulse trains are shown in Figs. 2(b), 2(c), and 2(d), respectively. The adjacent pulse amplitudes are nearly equalized (within 10% fluctuation) even at tenth-order rational harmonic condition. Note that this performance can further be improved by use of an intracavity fiber Fabry–Perot etalon filter with longitudinal mode spacing equivalent to the repetition frequency of the mode-locked EDFLs. However, the fiber Fabry–Perot etalon filter at a specified frequency is no longer suitable when the repetition frequency of the EDFL is widely detuned. In other words, the EDFL system may require several fiber Fabry–Perot filters with different longitudinal mode spacings when one is operating at different repetition frequencies. In addition, frequency multiplication cannot be observed when the EDFL is not in regenerative (closed-loop) amplification or injection-locking mode. The pulse width of the injection-locked EDFL at higher rational-harmonic frequencies can be further shortened to only 21 ps (at 10 GHz, or the tenth rational-harmonic order), as shown in Fig. 3. The pulse width was found to exhibit an inversely proportional dependence on the square root of the repetition frequency, somewhat similarly to conventional mode-locked fiber lasers (Fig. 3, inset). However, its peak amplitude decreases significantly to 500 mW (nearly 5-dB attenuation) as the repetition increases to 10 GHz. This result also correlates well with the characteristics of conventional microwave frequency multipliers. The signal-to-noise extinction ratio of the injection-locked EDFL measured from the mode-beating spectrum is as much as 40 dB.

The pulse width and power of the injection-locked EDFL are significantly degraded as the modulating frequency is positively or negatively detuned (even by

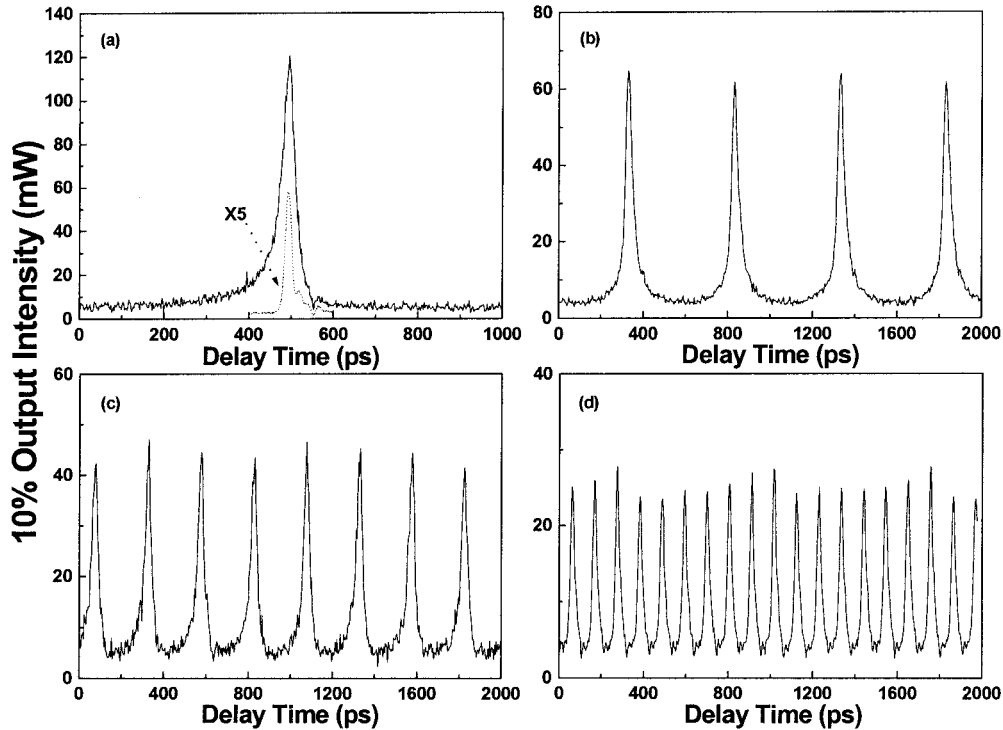


Fig. 2. Pulse-shapes of (a) an injection-locked EDFL and a gain-switched FPLD at 1 GHz and the injection-locked EDFL rational-harmonic repetition frequency multiplied at (b) 2 GHz, (c) 5 GHz, and (d) 10 GHz.

as little as 1 kHz) from the resonant frequency of the EDFL (Fig. 4, inset). By contrast, such a detuning result is not observed in a general EDFA system. The highest peak power is achieved at the exact matched-frequency (set as zero detuning) condition. The maximum frequency-detuning as well as injection-locking range⁹ for the EDFL is only -13 kHz (negative detuning) to $+27$ kHz (positive detuning). The GSLD pulse depletes the gain medium earlier than the circulating pulse as its repetition frequency is positively detuned, which inevitably decreases the peak power and broadens the pulse's trailing edge. The leading

edge of the pulse from the injection-locked EDFL lengthens significantly when the frequency is negatively detuned, however. The asymmetric pulse-width broadening behavior of the negative- and positive-detuning regions is attributed in particular to the asymmetric GSLD pulse shape (short rise time and long falling tail). The peak power of the injection-locked regenerative EDFA increases dramatically from 1.8 W to <500 mW within a detuning frequency of ± 5 kHz, which eventually disappears as the GSLD is frequency detuned beyond the injection-locking

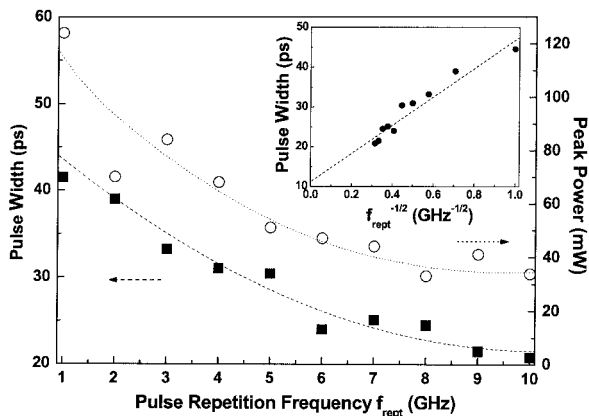


Fig. 3. Pulse width (filled squares) and peak power (open circles) of the injection-locked EDFL pulse repeated at several rational-harmonic frequencies. Inset, linear relationship of the pulse width to the reciprocal square root of the repetition frequency.

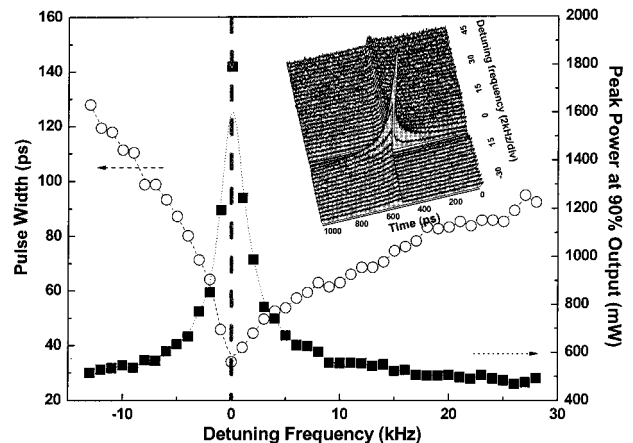


Fig. 4. Pulse width (open circles) and peak power (filled squares) of the injection-locked EDFL at several detuning frequencies. Inset, evolution of the EDFA pulse-shape at several detuning frequencies.

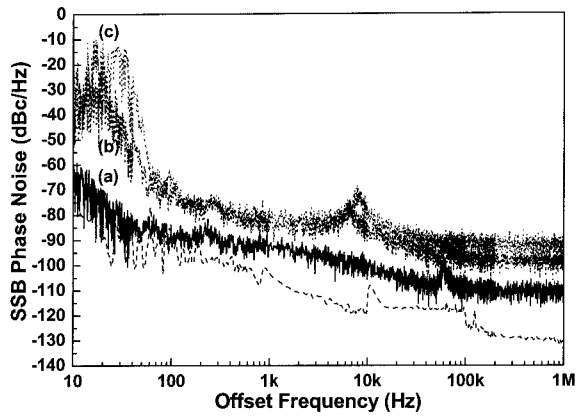


Fig. 5. SSB phase noise spectra of the EDFL pulse repeated at (a) fundamental (1-GHz), (b) 10th-order multiplied harmonic (10-GHz), and (c) 20th-order multiplied harmonic (20-GHz) frequencies. Dashed curve, phase noise of the driving electronics at 1-GHz frequency. Inset, corresponding timing jitter integrated from the phase-noise density spectrum at a repetition frequency of 1 GHz.

bandwidth of the EDFL. The pulse width is rapidly broadened to >90 ps after negative detuning by 5 kHz. By contrast, the pulse width broadening for positive detuning is relatively moderate. The injection-locked EDFL pulses first disappears and eventually tends to undergo frequency-multiplied increases as the GSLD frequency is adjusted further from the locking band edge and until it matches the rational-harmonic condition.

The SSB phase noise and associated timing jitter performance of the injection-locked EDFL pulses before and after frequency multiplication is determined. For example, the SSB phase noise and jitter of 1-GHz repetitive injection-locked EDFL pulses measured at offset frequencies from 10 Hz to 1 MHz are shown in Fig. 5. The SSB phase noise spectra of the EDFL pulses at repetition frequencies of 10 and 20 GHz after frequency multiplication are shown for comparison. Because of the relatively low and stable phase noise properties of the GSLD (~ 0.3 ps in general) at a relatively large frequency-tuning range, the SSB phase noise and the corresponding jitter of the injection-locked EDFL pulses can remain below -90 dBc/Hz and 1 ps, respectively, within the injection-locking range (from -13 to $+27$ kHz). It can be seen that the SSB phase noise is minimized to < -102 dBc/Hz at an offset frequency of 100 kHz and to ~ 0.3 ps in perfect injection-locking conditions. As the modulation frequency is detuned beyond the locking bandwidth, the SSB phase noise of the EDFL pulses increases dramatically owing to breakdown of the injection-locking process. The SSB phase noise becomes worse than -95 dBc/Hz as the GSLD frequency is detuned beyond ± 5 kHz, where the injection-locking mechanism is degraded. This leads to increasing jitter from 0.3 to 0.5 ps, as shown in Fig. 6. The stable detuning bandwidth for low timing jitter is not symmetrical in the positive and negative

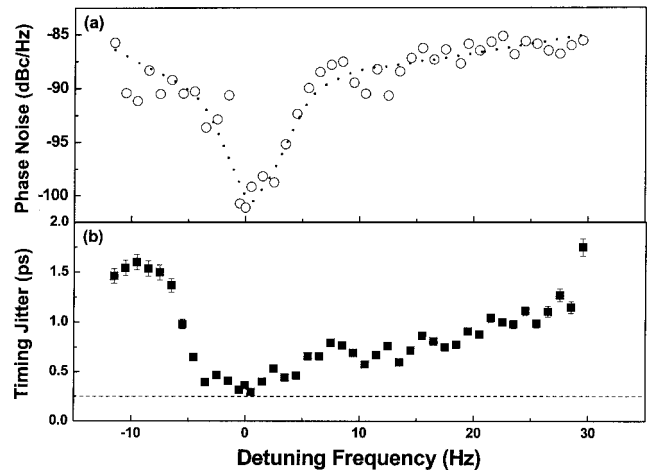


Fig. 6. Measured (a) SSB phase noise and (b) timing jitter of a fundamental injection-locked EDFL pulse train as a function of detuning frequency.

detuning regions because injection locking is broken up much more quickly at negative detuning.

We also compared these results with those in other laser systems previously reported. A relatively comparable frequency-detuning range of ~ 40 kHz was reported for a passively mode-locked EDFL obtained by harmonic injection-locking.⁴ Wen *et al.*¹⁰ demonstrated mutual injection-locking semiconductor lasers with SSB phase noise and timing jitter of -92.5 dBc/Hz and 0.4 ps, respectively. Kiyani *et al.*¹¹ reported an actively mode-locked EDFL with a locking range of 106 kHz by use of an integrated-optic-modulator based mode locker, which reveals that the mode-locking system may exhibit a much broader locking bandwidth than the injection-locking system. In particular, Gupta *et al.*⁸ also demonstrated mode-locked and regeneratively mode-locked EDFLs at 2 GHz with relatively low timing jitters of only 0.38 and 0.26 ps, respectively. We thus conclude that the optical-pulse injection-locked EDFL could benefit from comparable (or even better) phase noise and jitter performance at the cost of a narrower locking bandwidth. The timing jitter (integral within an offset frequency below 100 kHz) and the stable detuning bandwidth of rational-harmonic frequency-multiplied, injection-locked EDFL pulses at four repetition frequencies are shown in Fig. 7. The timing jitter increases by as much as 1.2 ps at a repetition frequency of 10 GHz, while the detuning bandwidth for low jitter response becomes narrower (from 30 to <10 kHz). This result is attributed to degradation of SSB phase noise during frequency multiplication (increasing by $10 \log N$, where N is the rational-harmonic order), which inevitably causes a serious phase slip between the circulating pulses and the pulsed gain modulation window on each round trip at such a high repetition frequency. The detuning bandwidth further decreases to <2 kHz as the multiplying frequency increases to 20 GHz, while the measurement of the exact detuning range is limited by the

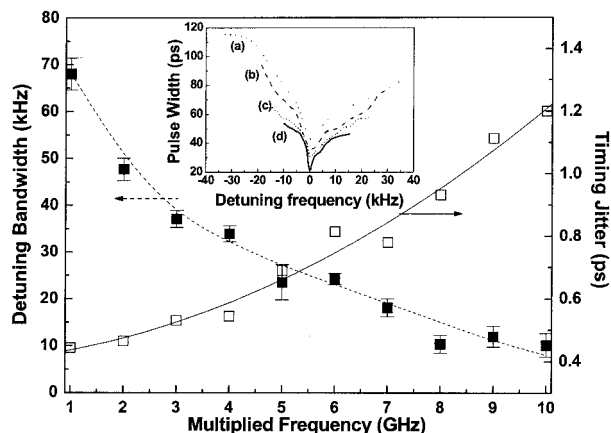


Fig. 7. Detuning bandwidth and timing jitter of an injection-locked EDFL at several multiplied repetition-frequency conditions. Inset, detuning-frequency-dependent EDFL pulse width at repetition-frequencies of (a) 1 GHz, (b) 2 GHz, (c) 5 GHz, and (d) 10 GHz.

frequency resolution of our electronics ($\Delta f = 1$ kHz). The timing jitter can no longer be calculated in this case because the phase noise at higher-order harmonics of the 20-GHz repetition pulse train is too small to be obtained by our optoelectronic instrument. Nonetheless, the reported timing jitters at repetition frequencies of <10 GHz are relatively comparable to those of typical mode-locked fiber lasers, which have met the demands of most applications.

4. Conclusions

With the injection of a GSLD at a repetition frequency of 1 GHz, the jitter and frequency-detuning dynamics of harmonic and rational-harmonic injection-locked regenerative EDFAs at repetition frequencies of 1 to 10 GHz have been reported. The GSLD pulse is 10-dB regenerative amplified but broadened from 17.6–41 ps in the injection-locked EDFL. A maximum injection-locking bandwidth of 40 kHz extending from -13 to $+27$ kHz was observed. The timing jitter of the injection-locked EDFL repeated at 1 GHz can remain unchanged (<0.5 ps) within a detuning frequency of ± 5 kHz. As the repetition frequency is multiplied from 1 to 10 GHz, the maximum frequency-detuning range of the EDFL decreases from 40 to 9 kHz and the injection-locked EDFL pulses become shorter (~ 21 ps) and smaller (0.3 W) because of the inevitably increased jitter of as much as 1.2 ps. A procedure that comprises optical-pulse injection locking and rational-harmonic fre-

quency multiplication may be an alternative for low-cost, high-bit-rate optical pulse generation from EDFLs that will yield a slightly narrower locking bandwidth but phase noise and jitter that are comparable to those of conventional mode-locked EDFL systems.

This study was supported in part by the National Science Council of the Republic of China under grant NSC91-2215-E-009-039.

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